Active Transport of Carbon Nanotubes Using Motor Proteins

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Motivation—Parallel and directed assembly of nanoscale building blocks is required to create nanodevices of practical significance. We are exploring the use of energy-consuming "nano-robots" – motor proteins and microtubules – for the active transport, assembly, reconfiguration, and healing of nanocomposites in artificial environments. As a model system, we are currently collaborating with Professor Robert Haddon's research group at the University of California, Riverside, to learn how to use motor proteins to manipulate single-wall carbon nanotubes (SWNTs) in microfluidic systems. The ultimate goal of the collaboration is to learn how to create arrays of programmable conductive interconnects.

Accomplishment—The geometry we have selected for promoting the active transport and assembly of carbon nanotubes (Fig. 1) is the so-called inverted motility assay. In this geometry, self-assembled monolayers containing the motor protein kinesin (pink) are anchored to an array of gold electrodes such that the mobile "feet" of the motors are available for binding to short segments of microtubules called shuttles (green). In the presence of adenosine triphosphate (ATP) "fuel", the motors propel the shuttles and any associated "cargo" across the substrate surface. Haddon's group has functionalized their carbon nanotubes (blue) with streptavidin (red arc), which forms a strong linkage with microtubules that we have functionalized with biotin (red ovals). As both the microtubules (25 nm diameter) and the typical bundles of carbon nanotubes (5-10 nm diameter) are too small to observe under normal circumstances, both components have been labeled with fluorescent dyes that allow them to be observed under a fluorescence microscope. We recently received the functionalized SWNTs from the Haddon group and have been able to: (1) disperse the SWNTs, which are normally agglomerated, (2) attach the SWNTs to our microtubules in solution, (3) adsorb the microtubules onto patterned gold electrodes, and (4) examine the adsorption and motility of the microtubule-SWNT constructs under the microscope. Images obtained to date (Fig. 2) clearly show that (1) the microtubules are almost exclusively adsorbed onto the gold electrodes by the motor protein monolayers, (2) the carbon nanotubes are bound exclusively to the microtubules (no free nanotubes are present), (3) single microtubules (which can be over 10 microns long) can span the gaps between electrodes, bridging the gaps with conductive carbon nanotubes, and (4) (not shown) although coated with SWNTs, the microtubules remain active and are propelled by the motor proteins in the presence of ATP fuel. Work will now progress to determining the electrical conductivity of the microtubule-SWNT bridges and learning how to program the microtubules to create and remove bridges on command.

Significance—SWNTs are regarded by many as the ultimate nanomaterial because of their unique electrical, optical, and mechanical properties. If we can learn how to manipulate SWNTs with motor proteins, we should be able to create and reconfigure complex, responsive networks of SWNTs using biomimetic strategies that are more versatile and controllable that existing techniques. For example, it is difficult to create such networks using current methods that involve physically picking up and placing each nanotube using nanomanipulators such as scanning probe systems.

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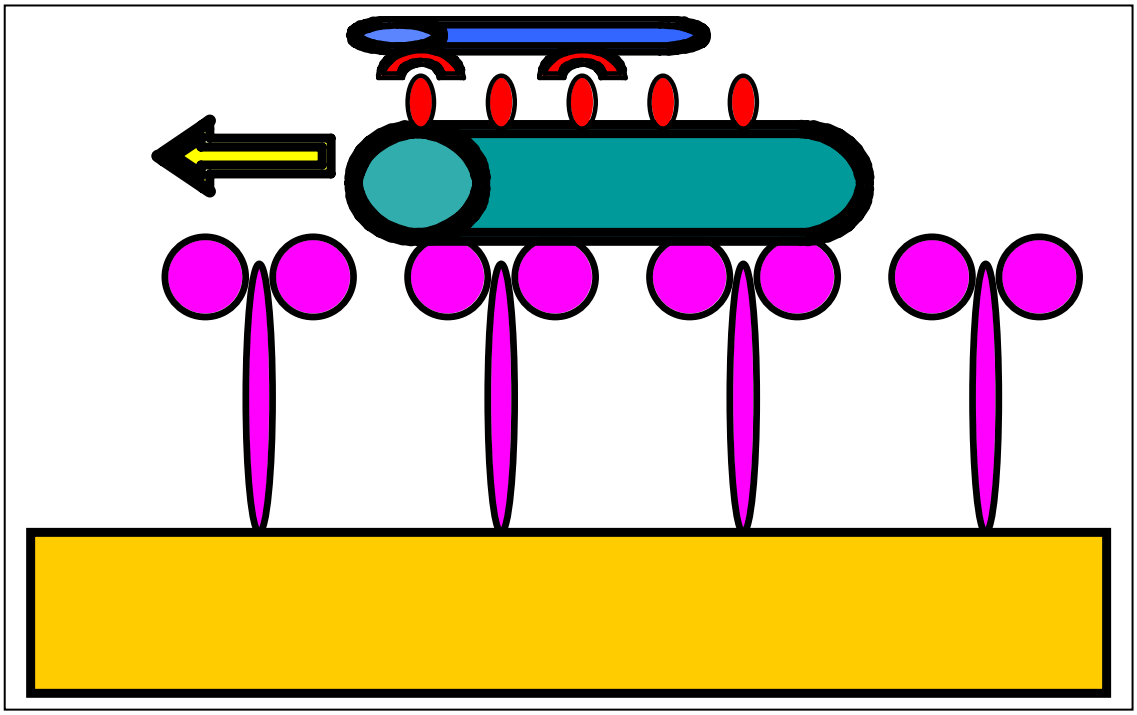

Figure 1. Depiction of the system used for the active transport of carbon nanotubes (blue) attached to microtubules (green) via the biotin-streptavidin linkage (red ovals to red arcs). Motion is provided when the "feet" of tethered motor proteins (pink) "walk" along and thereby propel the microtubule shuttles.

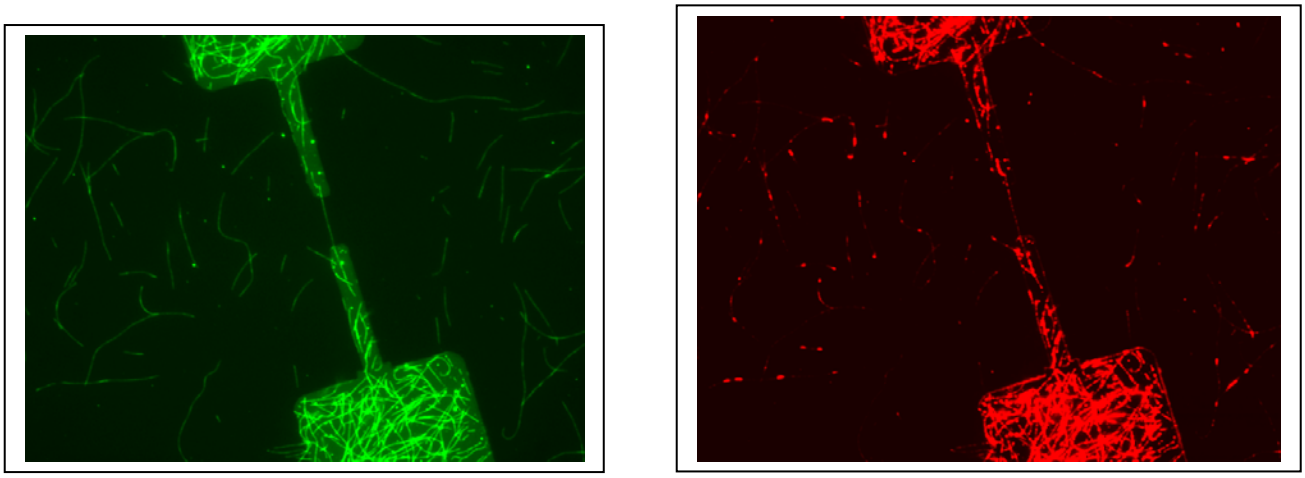

Figure 2. Fluorescence micrographs of microtubule-SWNT constructs bound via motor proteins to gold electrodes (square region is 25 microns across). Left – Fluorescence signal from the microtubules. Note that one microtubule spans the gap between the top and bottom electrodes. Right – Fluorescence signal from the carbon nanotubes. Note that all carbon nanotubes are associated with microtubules.